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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Ludwig-Maximilian University of Munich as follows: The contractor will build an extremely all-solid-state spectrometer operating from the GHz up to the lower THz frequency regime with Hertz-level resolution. This method is sensitive up to 400 GHz and will be used to investigate electronic systems of reduced dimension. The contractor will compare the performance of the spectrometer with other microwave sources including gunn oscillators, FIR laser systems and common HP Network analyzers, as well as a high-frequency spectrometer. To accomplish this research plan will consists of 4 phases: (1) Fabricate and assembler power combiner/planar antenna substrates; (2) Perform photoconductive experiments using the terahertz generation system; (3) Combine terahertz generation system with coupled semiconductor quantum dots; (4) Perform photoconductive experiments on a grid of individually tunable coupled semiconductor quantum dots.

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Ultrafast Solid State Spectrometer: Final Report

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Executive Summary

In the last years the continuing trend of shrinking semiconductor devices led to the discovery of single electron transistors (SETs) in which charge transport is governed by the Coulomb interaction of individual electrons. SETs in semiconductor host crystals are termed quantum dots or 'artificial atoms', due to the discrete excitation spectra observed in transport and microwave spectroscopy. A typical quantum dot diameter is by now of the order of 50 – 100 nm, containing a tunable number of 5 – 50 electrons. The main focus of research so far was taming the static dot-dot interaction and of the influences of their micro-environment. Naturally, it is now of prime importance to study the dynamics of these systems, since only a detailed understanding will allow to build ultrafast electronic devices functioning with only a few electrons.

By building quantum dots containing only about 15 electrons we were able to selectively address excited states in transport spectroscopy. By combining these classical methods with a newly developed wide band millimeter wave spectrometer, we achieved revealing the population dynamics of these excited states. This allows us by now to not only probe but also design the electron dynamics in these artificial structures. In this report, we review the main accomplishments of this project, with the details addressed in the appendices containing papers published with support from the sponsoring agencies.

Microwave Spectroscopy on Quantum Dots

In the last year, we fabricated several quantum dot systems and built a fully operational ultra wide band spectrometer from two single non-linear transmission lines. The dots were characterized by low temperature measurements (T ~ 25 mK), showing clearly excited states. In preliminary studies on coupled dot systems, we already found manifestation of large tunnel splitting. Finally, the spectrometer was applied for probing single quantum dots containing only ~15 electrons. By using strobe pulses with a typical duration of ~100 psec, we resolved charging of the ground and excited states of these dots. This gives us full control of the dynamics of the charging dynamics and dot's internal dynamics of shuffling electrons.

Specific accomplishments included:

- Microwave spectroscopy on a coupled dot applying conventional microwave spectrometry [1]
- Measurements on a single quantum dot with a preliminary setup [2]
- Applied the fully integrated non-linear transmission line spectrometer to measurements on a single quantum dot operated in the few-electron limit [3]

Conclusions and Future Directions

We successfully built, tested and applied a fully integrated ultra wide band spectrometer for investigating the dynamics of few-electron quantum dots. The spectrometer covers the frequency range of 20 – 400 GHz with sub-10 Hz resolution. Functioning of the new spectrometer was first tested on bolometer circuits enabling an estimate of the total emission power. We then realized a single few-electron quantum dot and performed transport experiments at low temperatures. Combining transport and our unique millimeter wave spectroscopy allowed us to study the dynamics of the single electrons confined in the quantum dot. We want to further apply this technique for studying the dynamics of single electrons in coupled quantum dots. The resolution already achieved for single dots should allow us to reveal the interaction processes of these artificial molecules with extremely high resolution.

References and Appendices

[1] H. Qin, A.W. Holleitner, K. Eberl, and R.H. Blick, "Superposition of photon and phonon assisted tunneling in coupled quantum dots", *submitted to Physical Review Letters* (2000). .

[2] H. Qin, F. Simmel, R.H. Blick, J.P. Kotthaus, W. Wegscheider, and M. Bichler, " Photoconductance measurements in the non-linear transport regime of a few-

electron quantum dot using phase-locked microwave sources," *Physical Review B, Rapid Communication, in press* (2000).
[3] Q. Hua, R.H. Blick, D.W. van der Weide, and W. Wegscheider, " Wideband Millimeter-wave Spectroscopy on a Single Quantum Dot", *submitted to Science* (2000).

Ultrafast Solid State Spectrometer: Half Time Report

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Executive Summary

The use of ultrafast semiconductor devices demands the development of adequate sampling circuits. The smallest transistors realized today, so called quantum dots, contain only 20 - 200 electrons and are built with feature sizes below 50 nm. The switching times of electrons in these quantum dots, however, are not understood in detail, since no appropriate spectroscopic tool was available so far.

We have developed such a tool, which should allow us in the near future to probe electronic states in single and coupled quantum dots. This tool is a wideband millimeter wave spectrometer operating in the frequency range of 1 - 400 GHz with sub-Hz resolution. In the on-going work we realized a wideband millimeter wave spectrometer in a compact design: The core of this spectrometer is formed by two phase locked non-linear transmission lines (NLTLs) as shown in Fig. 1. These two ultrafast circuits produce beats of radiation with frequency components up to 400 GHz. The output of the two sources is coupled by coplanar wave guides and fed into a slot antenna radiating into free space via a silicon hemisphere on the back plane of the circuit. Although impedance matching for the whole circuit is of great importance, we are still able to detect nW output power due to the immense sensitivity of the quantum dots used in this experiment.

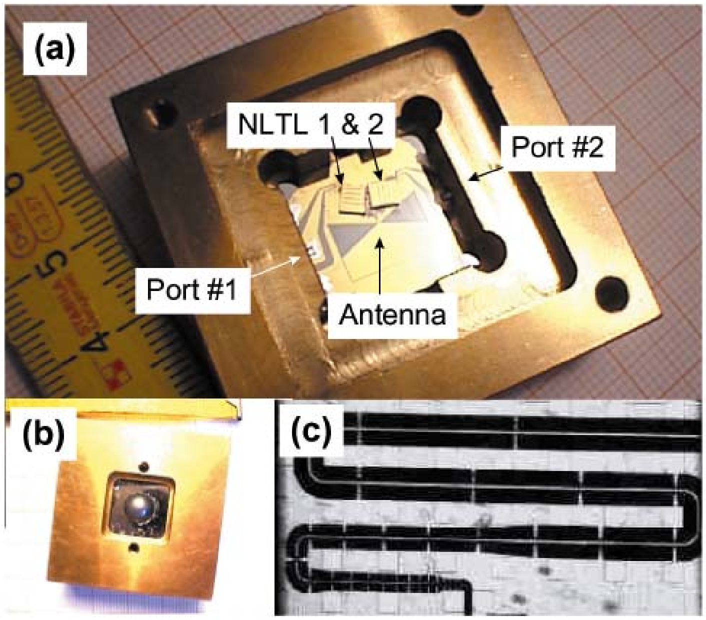

Fig. 1: The wideband millimeter wave spectrometer: (a) Two nonlinear transmission lines (NLTLs) integrated in the power combiner are fed through ports #1 and #2 with microwave radiation. (b) View from below with the silicon lens on the circuit backside. (c) Close-up of one of the NLTLs.

In this report, we briefly review the status of this project, with the details addressed in the paper. More results through the coming final half of the year are expected as we bring the first NLTL spectrometer into action on quantum dots with support both from this program and from the German ministry for science and technology (Bundesministerium für Wissenschaft, Forschung und Technologie, BMBF).

Wideband Millimeter Wave Spectrometer

In preliminary experiments without the NLTLs with a small single dot containing about 25 electrons, we found that tracking single electron tunneling under millimeter wave radiation with two phase locked synthesizers allows us to monitor excited states in the nonlinear transport regime [Qin99]. In this case we applied an identical setup as planned for the NLTL-spectrometer, except that we removed the NLTLs. Hence, we basically obtained a modulated continuous wave radiation being radiated onto the quantum dot under investigation, where the energy of the millimeter wave radiation was on the order of 10 - 40 GHz, while the signal is modulated with 1 - 10 kHz.

The obtained spectra are then compared in detail to the ones found in dc transport spectroscopy. This allows us to differentiate between microwave induced states and slowly decaying ground states. However, this method has a considerable disadvantage compared to the NLTL spectrometer in that it does not allows time resolved measurements. This is possible now with the pulsed output of the NLTLs with sub-Hz resolution.

Specific accomplishments included:

- Developed first compact NLTL spectrometer (see Fig. 1)
- Measurements with NLTL spectrometer on bolometers for calibration purposes
- Characterized quantum dots with rump NLTL spectrometer [Qin99]

Conclusions and Future Directions

In the next future we plan to apply this spectrometer to measurements on single and coupled quantum dots. This will elucidate the intricate dynamics of single electrons in these few electron systems. In particular we hope to determine the relaxation times of excited states directly and to analyze phase coherent relaxation processes. Moreover, we plan to extend our setup by using synthesizers capable of generating output frequencies in the range of 10 MHz to 50 GHz and thus the frequency range of operation of the NLTLs to above 500 GHz.

References and Appendices

[Qin99] H. Qin, F. Simmel, R.H. Blick, R. H. Blick, J.P. Kotthaus, and K. Eberl, ”Photoconductance measurements in the nonlinear transport regime of a few-electron quantum dot”, submitted to *Physical Review B*, Rap. Comm. (1999); cond-mat/ 0003170.